Hot-wire anemometer based on fiber Bragg grating coated with carbon conductive paint

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Hot-wire anemometers are sensors used to measure wind speed via the principle of thermal equilibrium. They are attributed to the issue of probe contamination, requiring regular maintenance, causing inaccurate measurements. A hot-wire anemometer based on FBG coated with carbon conductive paint is proposed. 2 mm coating is applied on the FBG grating region using brushing method. The sensitivity of the proposed anemometer is 0.0410 nm / (m/s) in the temperature range of 60 °C to 150 °C, at wind speeds of 0 m/s, 4.55 m/s , 4.86 m/s and 5.02 m/s. The FBG is proven to possess increased sensitivity towards temperature, improving its thermal anemometry capabilities.

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1. Introduction

Wind flow measurement has been a significant method in real world applications due to their importance in monitoring environmental conditions, such as in aviation, wind farms, weather forecasting, marine, aerospace and automotive-based professions [1, 2]. Since the invention of the first cup anemometer by T. R. Robinson in 1847, the development of wind measurements has advanced steadily with emerging new technologies utilizing mechanical and optical-based sensors.

Fiber Bragg grating (FBG) has been gaining interest due to its potential in sensing application. Due to its properties of being low cost, compact, highly sensitive and good performance over a wide range of bandwidth as well as being immune to electromagnetic waves, FBG is an ideal option to be used for mechanical and electronic based sensors [3]. This includes the applicability of FBG sensor in harsh conditions and environments [4]. There have been several FBG-based anemometers reported, which commonly apply hot-wire anemometry. Hot wire anemometry basically is a fluid velocity measurement technique based on the convective heat transfer between a heated wire, which in this case is between the FBG and the fluid flow.

In previous work, the sensitivity of the thermal part of the anemometer is enhanced through the application of a metal film on top of the FBG. In 2012, a silver film-coated FBG with a core offset fusion splice was demonstrated as a compact anemometer, which achieved a sensitivity of 45.3 pm / (m/s) at wind speeds up to 6 m/s [5]. Another improvement was made in 2019, with the inclusion of a waist-enlarged optical fiber bi-taper and cladding-etched on the FBG coated with a silver film with a recorded sensitivity of 696.3 pm / (m/s) and 35.5 pm / (m/s) at speed below 1.5 m/s and 6.9 m/s respectively [2]. Another study in 2022 revealed that by reducing the diameter of the fiber cladding etching, the sensitivity of the anemometer was improved by 3.8 times [6].

Recently, the emergence of carbon conductive paint as a coating substance on FBG has been investigated. Carbon conductive paint is a material that can be used on top of materials to give them conductive properties and be used as parts in electrical circuits such as resistors, electrodes and conductors. The process to fabricate the coated FBG can be simply done through a brushing method. Compared with other types of conventional metal coatings that is used in FBG sensors, it is considered a better option given its abilty to provide excellent electrical conductivity that is durable, resistant to corrosion, cost effective with ease applications in various conditions and harsh environments [7, 8]. In 2021, it was reported that the 3 mm coated FBG demonstrated 4 times the sensitivity over a bare FBG when it comes to temperature measurement [9]. A similar study also showed that with increasing coating thickness, the sensitivity of the temperature sensor can be increased as well [10]. The applications of carbon conductive paint for FBG sensors has been proven to enhance the sensitivity in measuring the changes of voltage in certain environments [11, 12].

In this paper, a hot-wire anemometer based on FBG coated with carbon conductive paint is conducted. The carbon conductive paint is applied on the grating region, which is the sensing part, and heated at a certain temperature. The coated FBG is then exposed to an incoming wind which cools down the sensing region. The shifting of the Bragg wavelength is measured throughout the experiment, followed by the sensitivity measurement and calculation of the sensor with respect to an incoming air flow.

2. Experimental setup

Conductive paint is a paint that is infused with conductive materials that allow for electric conductivity when applied on a nonconductive surface. The main components of conductive paint are conductive particles, a liquid medium and a binder. Conductive particles can be based on metals such as copper and silver, or from carbon-based materials such as graphite and carbon black. Both materials enable the paint to exhibit its ohmic behavior and heat conductivity [13]. A binder is used to contain the conductive particles in a liquid based medium. There have been several studies that have investigated the viability of using conductive paint as a coating material on FBG to develop a sensitive temperature sensor that can be utilized in high temperatures and easy to fabricate [10].

Fig. 1 shows the experimental setup for the FBG coated with carbon conductive paint as a hot-wire anemometer. The setup consists of an SLD Broadband Light Source, FBG sensor, optical interrogator, 3-port optical circulator, heat plate, thermocouple and computer. An SLD Broadband Light Source (BBS) is used to produce a spectrum ranging from 1525 nm to 1570 nm and connected to port 1 of the 3-port optical circulator. The FBG sensor used in this experiment is connected to port 2 of the optical circulator. Before coating, the FBG sensor possesses a center wavelength of 1546.1568 nm at room temperature. Port 3 of the optical circulator is connected to the optical interrogator, which is also connected to laptop for data recording and measurement. The optical interrogator has scan frequency of 5000 Hz per channel with the wavelength repeatibility of +/-3pm and a wavelength resolution of 1 pm. For the coating process, a mixture of carbon conductive paint and water is applied on the grating region by using a brush and let to dry. This is done to allow the coating to cure properly. The process is repeated until the coating achieved a thickness of 2 mm. This thickness is reported to produce the maximum sensitivity for temperature characterization of conductive paint coated FBG [10].

The FBG sensor is placed on top of a heating plate (BHP-1610, Butterfly) inside a wind tunnel. A thermocouple (USB-TC01, National Instruments) is placed on top of the hot plate to monitor the current temperature inside the wind tunnel. The thermocouple is let to heat rapidly, reaching a temperature of 180 °C. As the temperature reaches at a range from 150 °C to 60 °C, measurements are taken. This is due to the cooling process is more controlled and allows for proper data collection procedures. The experiment is repeated by increasing the wind speed from 0 m/s to 5.02 m/s in the wind tunnel. For comparison purposes, the whole experiment is repeated with another bare FBG of the same grating length with a center wavelength of 1553.1873 nm as the FBG sensor, which will act as a control.

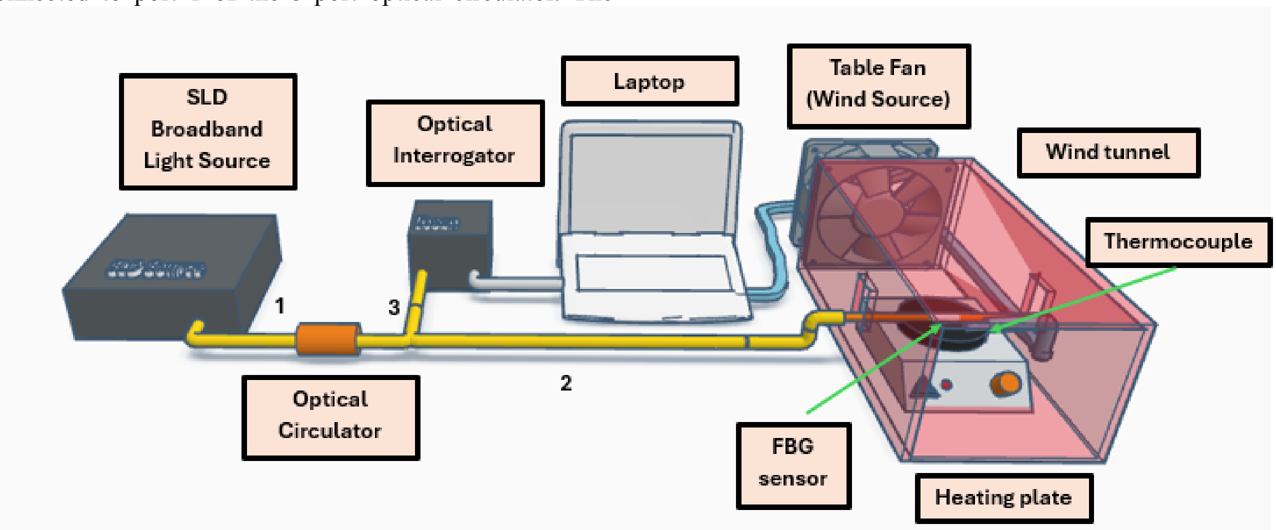

Fig. 1. Experimental setup of hot-wire anemometer based on FBG coated with carbon conductive paint (colour online)

3. Results and discussion

A. Carbon conductive paint coated FBG characterization

Fig. 2 shows the wavelength shift of the pre-coated and post-coated FBG sensor with conductive paint in ambient temperature. An average wavelength reading is at 45 seconds. The average wavelength of the pre-coated FBG sensor is 1546.15 nm. The post-coated FBG sensor shows the average wavelength of 1546.17 nm. This increment indicated that the conductive paint exerts an additional weight on the FBG sensor, causing the red shift of the Bragg wavelength. In terms of the response, the pre-coat and post-coated FBG sensor showcases similar ranges of 0.01 nm.

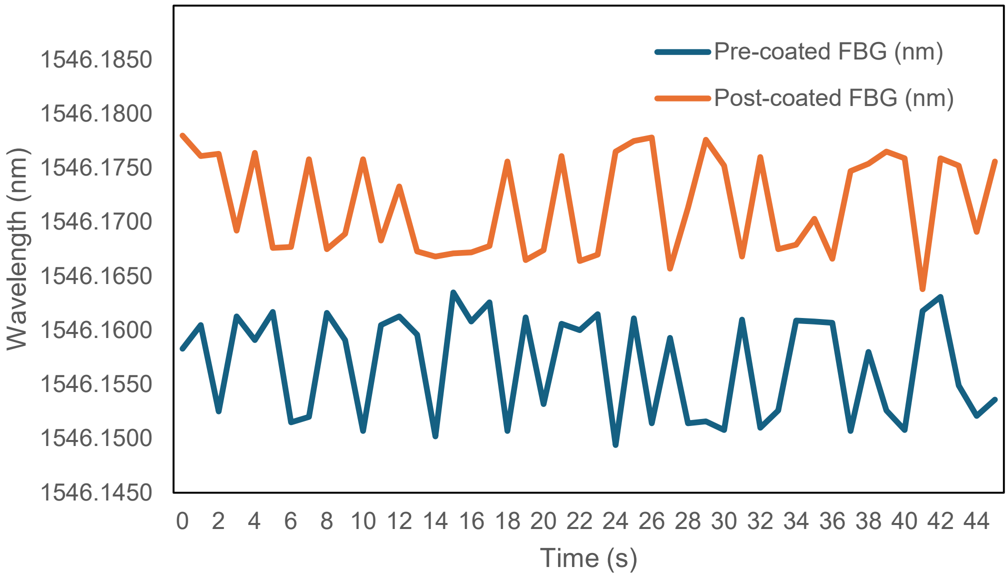

Fig. 2. Wavelength shift (nm) of pre-coated and post-coated FBG vs Time (s) (colour online)

B. Cooling temperature characterization

Fig. 3 shows the wavelength shift experienced by the coated FBG and control FBG under the influence of temperature. For comparison purposes, the difference of their respective wavelength shift is plotted on a same normalized axis in Fig. 4. The coated FBG exhibits a wavelength shift of 0.38 nm, from 1546.6239 nm to 1546.2425 nm, with the sensitivity value of 0.0043 nm / °C. On the other hand, the control FBG exhibits a wavelength shift of 0.16 nm, from 1553.1873 nm to 1553.0250 nm with normal sensitivity value of 0.0018 nm /°C. Considering the significant difference between the sensitivity of the coated FBG as compared with control FBG, this shows that coated FBG's response to temperature is more noticeable over the control FBG.

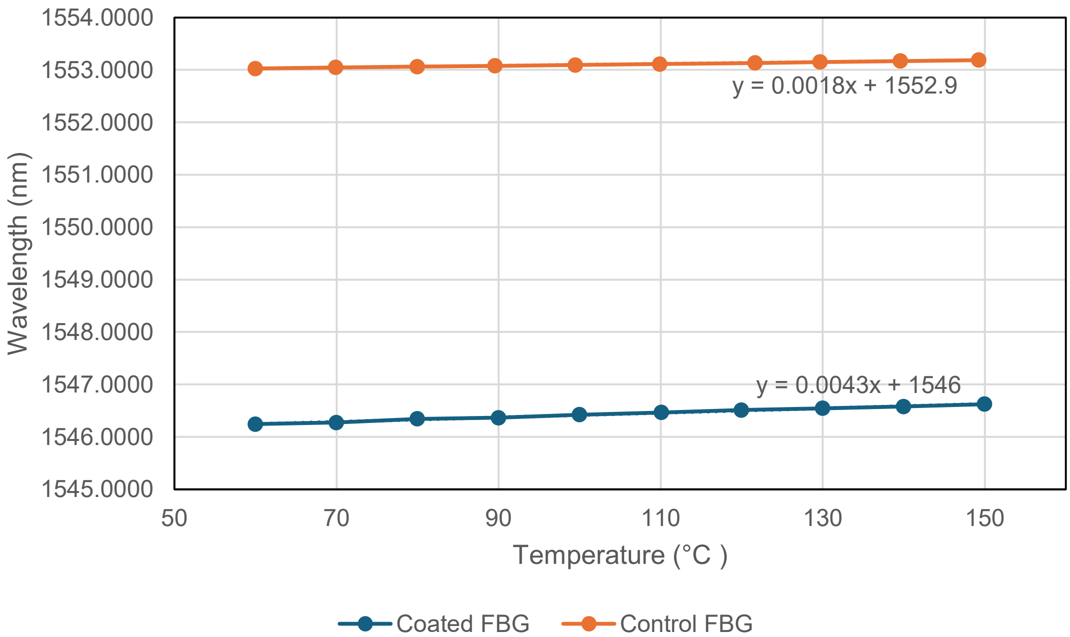

Fig. 3. Wavelength shift of coated and control FBG (nm) vs temperature (°C) (colour online)

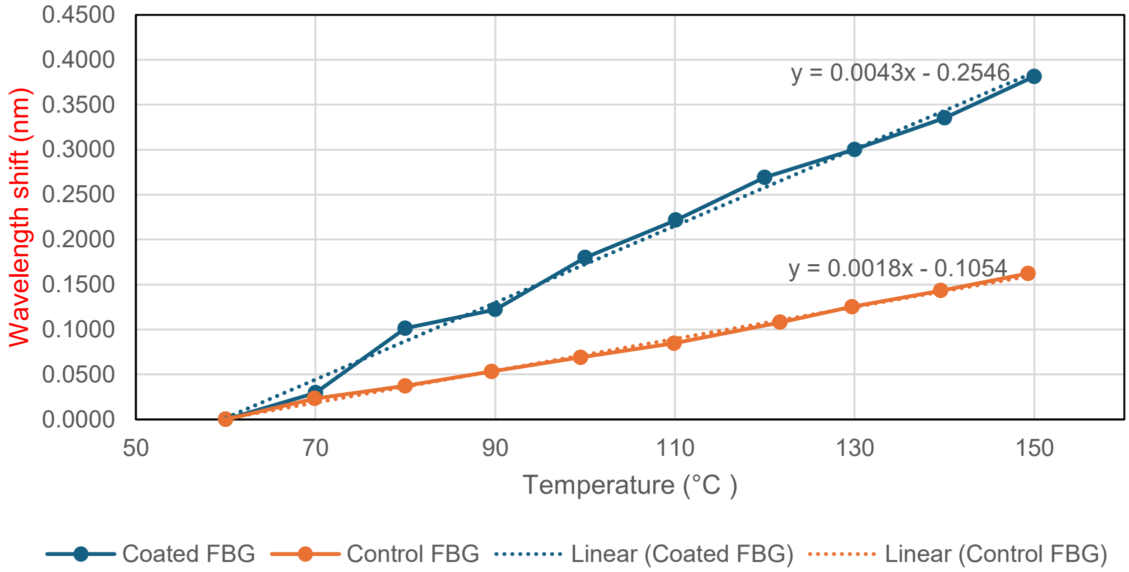

Fig. 4. Normalized wavelength variation coated and control FBG (nm) vs temperature (°C) (colour online)

The changes of temperature around the FBG surrounding causes the FBG to undergo thermal expansion, or in this case thermal contraction which causes the refractive index of the grating to change. The conductive paint has a higher thermal coefficient than the silica which contains the FBG. Due to this difference, stress is produced on the fiber, therefore altering the Bragg wavelength [14]. The thermo-optic effect also plays a role on the shift of Bragg wavelength as the change in refractive index affects the propagation constant of light that is supplied by the broadband SLD source. Both the coated FBG and control FBG experiences these effects.

The coated FBG however, has the inclusion factor of the conductive paint coating. The coating itself has become part of the strain in which the FBG experiences. As the temperature around rises, the coating expands, which in turn increases the spacing region of the Bragg wavelength. Conversely, as the coated FBG cools down, the coating region releases heat and contracts. This constricts the spacing of the grating region, decreasing the Bragg wavelength [11].

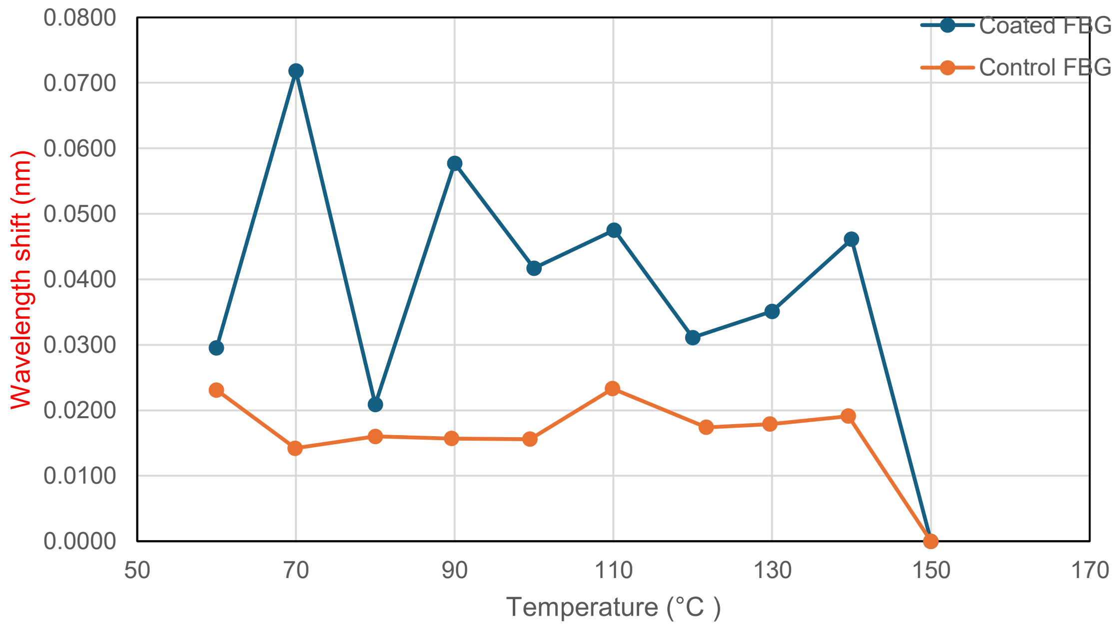

Fig. 5. Magnitude of wavelength shifts with respect to temperature intervals (°C) for coated and control FBG (nm) (colour online)

Fig. 5 shows the magnitude of wavelength shifts of the coated FBG and control FBG experienced during cooling from 150 °C to 60 °C. On average the coated FBG displays the higher wavelength shifts (0.0424 nm) over the control FBG (0.0180 nm). However, the former wavelength shifts were not as consistent compared to the latter, with range 0.0509 nm. The control FBG showcases a more consistent pattern throughout the cooling period with range 0.0091 nm. The contrast is attributed to a non-uniform coating on the grating region on the coated FBG, which causes heat to be released with fluctuating rates. As a result, the coated FBG's response towards the varying contraction rate of the conductive paint and thus the wavelength shift varies accordingly, compared to the bare control FBG.

C. Wind characterization

A conventional fan with three speed modes is used as the wind source. The values of each respective speed modes are 4.55 m/s, 4.86 m/s and 5.02 m/s, which are measured by a digital anemometer with resolution of 0.01 m/s. Fig. 6 shows the wavelength shift experienced by the coated FBG under the influence of temperature difference in multiple speed conditions. Based on the figure, the graph shows a nonlinear relationship with respect to wind speed at all temperature tested. Fig. 7 shows the wavelength shift experienced by the control FBG under the influence of the same temperature difference in the same multiple speed conditions. This figure also shows the same nonlinearity behaviour relationship with respect to the wind speeds for all the tested temperature.

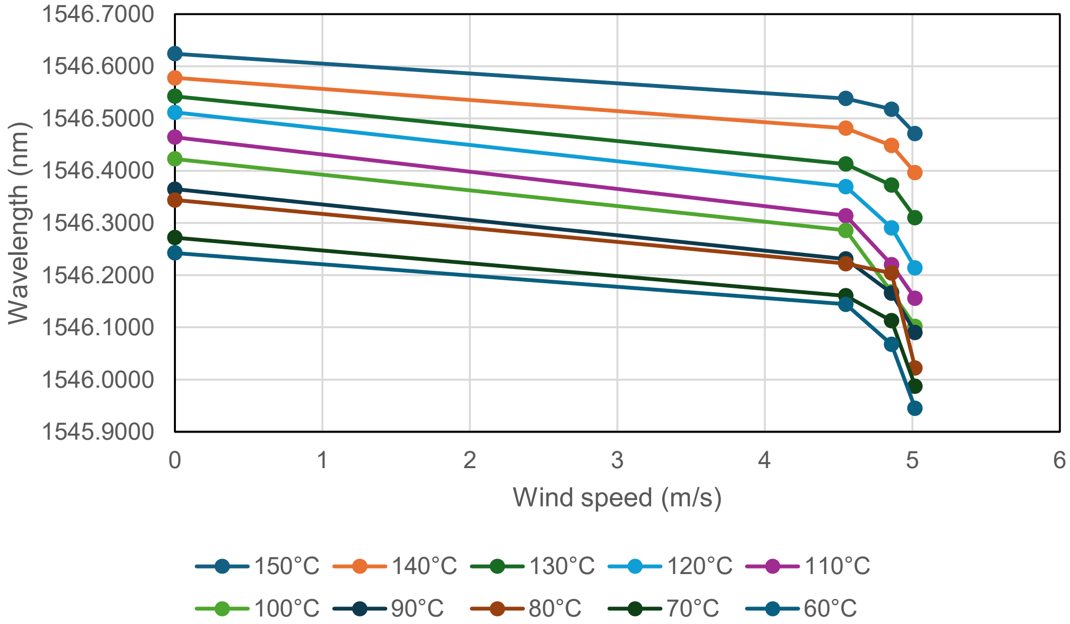

Fig. 6. Wavelength shift of coated FBG (nm) vs wind speed (m/s) at various temperatures (colour online)

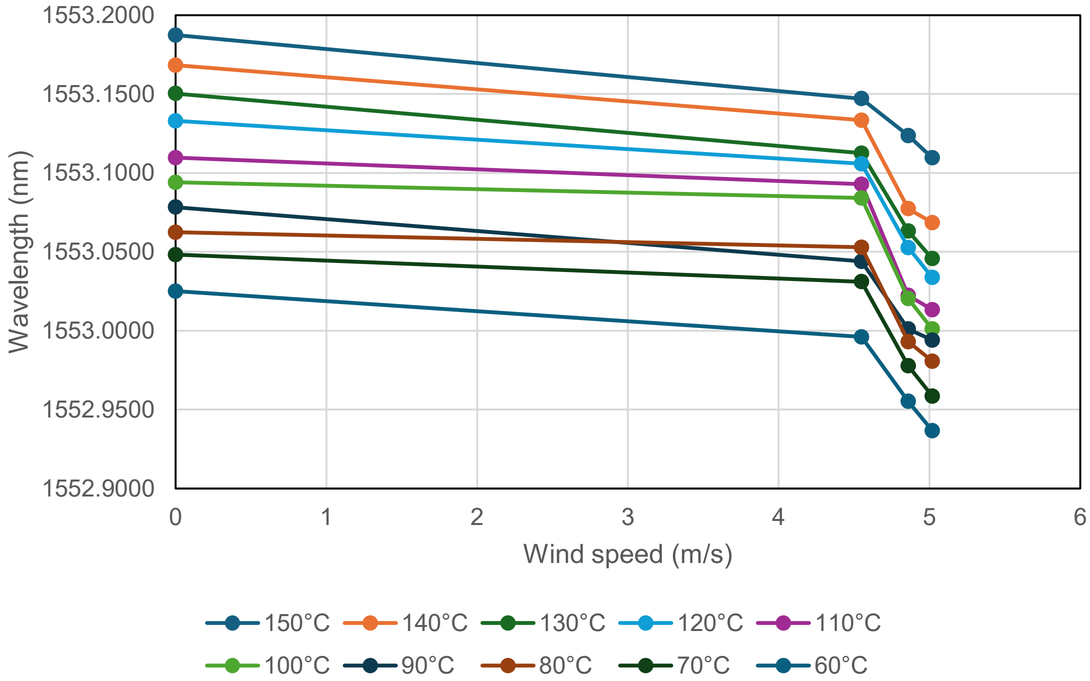

Fig. 7. Wavelength shift of control FBG (nm) vs wind speed (m/s) at various temperatures (colour online)

Both coated and control FBG sensors exhibits similar trendlines, where the wavelength decreases as the wind speed detected by the FBG increases. The higher wind speeds carry away the surrounding heat around the hot-wire anemometer. The FBG's response towards decreasing temperatures is reflected in the decrease of the wavelength shift as demonstrated in part B, where the grating period experiences thermal contraction. The sharp decrease of the wavelength shifts at wind speed above 4.55 m/s denotes that the FBG sensor is extremely sensitive at measuring wind speed, even at a difference as small as 0.16 m/s. Based on the plots, both FBG sensors has not reached their saturation point yet, and therefore is capable of measuring higher wind speeds until the FBG's strain limit is reached [15]. Apart from one data set in Fig. 6, all trendline are consistent with respect to each temperature intervals, as initial wavelength readings are observed at higher temperatures when no wind speed is present.

A comparison profile of average sensitivity of both sensors under the influence of constant wind speed for different temperature is shown in Fig. 8. The average sensitivity of the coated FBG as a hot-wire anemometer is 0.0410 nm / (m/s), while the control FBG's average sensitivity is 0.0143 nm / (m/s). On average, the coated FBG is 2.87 times more sensitive than control FBG under the presence of wind speed that were tested.

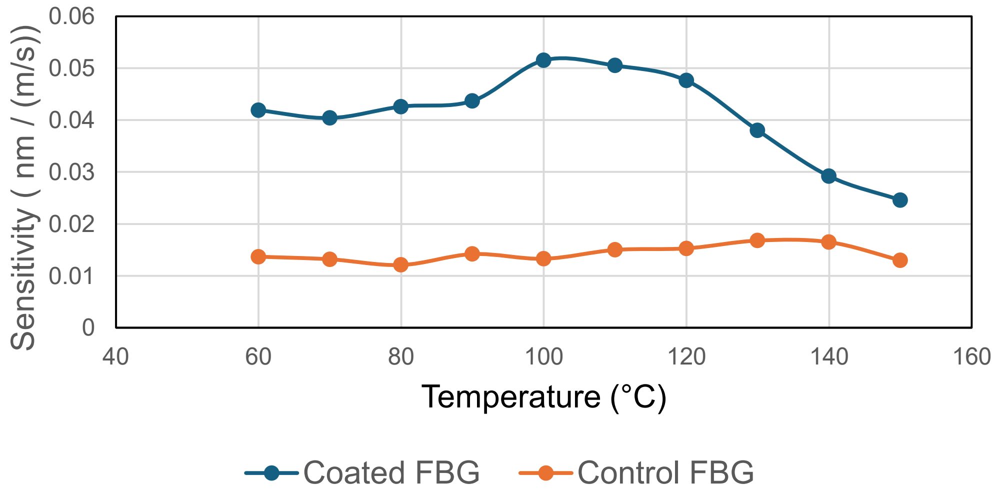

Fig. 8. Sensitivity comparison between the coated FBG and control FBG at various temperatures (colour online)

As wind speed increases, the heat that is contained inside the coating dissipates faster into the surroundings, therefore causing the coating to grip more into the grating region and shifting its wavelength even further. The control FBG is unaffected by any strain from the coating, therefore experiencing a somewhat stable but small increase in its sensitivity of wavelength shifts against rising wind speeds.

The ranges of sensitivity that were recorded by both FBG at temperatures above 90 °C is more turbulent than that of below 90 °C. At higher temperatures, the heat transfer to the surrounding is more rapid than at lower temperatures. Over the course of one second, which is also the recording interval of the thermocouple, the temperature change is too rapid, causing the Bragg wavelength change to be erratic. On the contrary, in temperature conditions nearing ambient temperature, the rate of heat transfer to the surrounding is slower, which meant that the gratings were able to shift downwards steadily.

D. Comparison of sensor's performance

There have been several works when it comes to incorporating FBG as part of a thermal anemometer. In 2011, an FBG based anemometer was proposed in which the gratings were inscribed inside a cobalt-doped fiber. The anemometer sensitivity was determined to be about 0.083 pm / (m/s) for speed ranges between 2 m/s to 8 m/s [16]. Another research work of the same year reported an optical thermal anemometer which combined both long period grating and FBG on a silver coated fiber. Based on the numbers provided, the sensitivity of the flowmeter shown in this paper is deduced to be at 120 pm/(m/s) [17].

In 2012, a thermal anemometer based on an FBG coated with silver film along with a core-offset fusion splice was proposed. A constant current configuration approach was used, in which a linear response of 45.3 pm/(m/s) for airflow velocity below 6 m/s was observed [5]. Two years later, the same group of researchers made an improvement on the predecessor sensor by using a silver coated FBG with a waist-enlarged fiber bitaper. It was reported that the improved sensor has higher mechanical strength and more stable coupling efficiency which achieved a higher sensitivity value of 47.2 pm/(m/s) [18]. A paper in 2016 proposed an FBG based anemometer that is inscribed in a metal-filled microstructured optical fiber. The reported sensitivity value of this anemometer was about 91 pm/(m/s) with laser pumping power of 11.5 mW at the wind speed of 2 m/s [19].

In 2017, a thermal anemometer based on TFBG coated with single-walled carbon nanotubes (SWCNT) is proposed. The resulting sensitivity of the thermal anemometer was measured to be about 366.7 pm/(m/s) at wind speed 1.0 m/s, with a TFBG tiled by 12° and 1.6 µm film, with output power of 97.76 mW [20]. Another work in the same year, the same single-walled carbon nanotubes (SWCNTs) coated tilted fiber Bragg grating (TFBG) with low power consumption was demonstrated, reporting a sensitivity of 34.6 pm/(m/s) at wind speed of 1 m/s, with output power of only 22.97 mW [21].

In 2019, a cladding-etched optical fiber Bragg grating (FBG) coated with a layer of silver film is proposed. The proposed thermal anemometer resulted a sensitivity of 696.3 pm/(m/s) for velocity under 1.5 ms [2]. This work which id the FBG hot anemometer sensor coated with conductive carbon paint produces an average sensitivity of 41.0 pm/(m/s) for range of wind speeds between 0 to 5.02 m/s. Although the sensitivity produced is lower than the rest of the studies, however cosiderations need to be taken regarding the coating material which has an upper hand as compared to other coating materials used. Thus, the option of using this carbon conductive paint as coating material in FBG based hot wire anemometer sensor is deemed plausible.

Table 1. Comparison of sensor's performance

Authors	Sensor description	Sensitivity (pm/(m/s))	Resolution (m/s)	Tested Wind Speed Range (m/s)
Gao et al., 2011 [16]	FBG inscribed on a cobalt-doped fiber	83.3 for v = 2 m/s to 8 m/s	0.012	0.0 – 8.0
Caldas et al., 2011 [17]	LPG and FBG inscribed on a fiber optic	120 for LPG with Λ = 385 µm	0.08	0.0 – 5.0
Dong et al., 2012 [5]	FBG coated with silver film with core-offset fusion spliced fiber	45.3 for v < 6 m/s	0.022	0.0 – 17.3
Wang et al., 2014 [18]	FBG coated with silver with waist-enlarged fiber bitaper	47.2 for v = 1.7 m/s to 5.3 m/s	0.021	0.0 – 13.7
Wang et al., 2016 [19]	FBG inscribed on a metal-filled (Bi-Sn-In alloy) microstructured optical fiber	91 for v = 2 m/s	0.011 for v = 2 m/s	0.0 – 2.5
Zhang et al., 2017 optics express [20]	TFBG coated with single-walled carbon nanotubes	366.7 for v = 1 m/s	0.0027 for v < 1 m/s	0.0 – 2.1
Zhang et al., 2017 sensors [21]	Single-walled carbon nanotubes (SWCNTs) coated tilted fiber Bragg grating (TFBG)	34.6 at v = 1 m/s	0.029	0.0 – 2.0
Chen et al., 2019 [2]	Cladding-etched optical fiber Bragg grating (FBG) coated with a layer of silver film	696.3 for v < 1.5 m/s	0.029	0.0 – 20.0
This work	Conductive paint coated on FBG	41.0 at v = 0 – 5.02 m/s	0.010	0.0 – 5.02

4. Conclusion

The performance of conductive paint coated on FBG as part of a hot-wire anemometer was presented. The brushing method was used to coat the FBG, which was repeatedly applied layer by layer and left to dry until the desired thickness was achieved. A comparison of the FBG spectrum before and after coating was made. The responses of the coated and uncoated FBG towards wind speed up to 5.02 m/s were measured in temperatures ranging from 60 °C to 150 °C in a cooling manner. An average sensitivity of 0.0410 nm / (m/s) has been achieved for the coated FBG, which is 2.87 times better than the bare FBG. The demonstrated anemometer is comparable to other FBG based hot-wire anemometers, showcasing similar sensitivity while being easy to fabricate. Future works will focus on testing various types of conductive paint and using different thickness coating on the FBG.

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